

PHOTOMASK

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Actinic EUVL mask blank inspection and phase defect characterization

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ABSTRACT

We have developed an actinic full-field mask blank inspection system to detect multilayer phase defects with dark field imaging. Using this system a non-commercial mask was inspected and real defects were detected by setting the system at low false detection threshold. A 1.5 mm square area (containing no absorber) was inspected three times, and probabilities of defect detection and false detection were evaluated. Of the total number detected, 81.5 % of them exhibited 100% percent probability of detection, while 0.8 % of them indicated false detection. The same area was also inspected with a conventional inspection system, and both inspection results then were compared. Among the defects detected, 94 % of them could be detected only with the actinic system, while 1.1 % of them could be detected only with the conventional laser-based inspection system. The detected defects were observed with AFM and SEM. In summary, phase defects smaller than 100 nm could be detected only with the actinic system, while particles smaller than 200 nm could be detected only with the conventional system.

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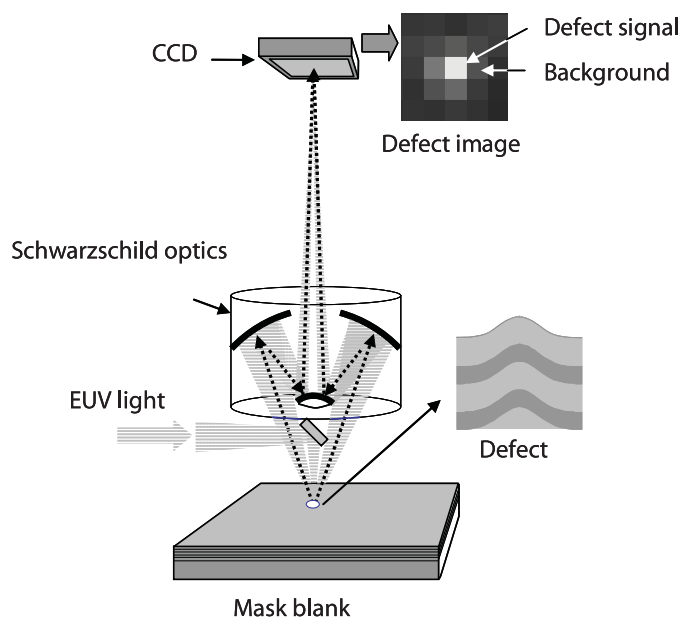


Figure 1. Actinic inspection of multilayer mask blank with dark-field imaging 3.

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EDITORIAL

In tribute to the many mask-makers who have left the industry in the past year...

Kurt R. Kimmel, Advanced Mask Technology Ctr. GmbH & Co., KG (Germany)

I consider myself fortunate to be living for the last two years in Dresden, Germany which is the most beautiful small city I have ever been to. My family was hosting some American high school student visitors recently and we took them for the requisite tour of the old city where one finds a postcard perfect 17th -18th century scene at every turn. We visited the palace of King Augustus II the Strong and the famous "Grünes Gewölbe" (the "Green Vault") which houses his most prized possessions. This mind-boggling array of objects is a testament to art, engineering, and craftsmanship. I deliberately use the word "objects" because in the collection are things ranging from carved crystal tankards, to jewel encrusted seashells, to intricate cameos carved from cherry pits, to various timepieces in gold or ivory operated by gravity. The spectrum of "stuff" in the Green Vault has a few common attributes: all are extravagant, expensive, exquisitely executed and, except for the clocks, fairly useless. Here was a man who had significant financial resources and interest in art. The market responded with craftspeople from all over Europe descending upon Dresden – "The Florence of the Elbe" – to take the opportunity to be an artist and being able to eat.

I realized that the fine work displayed, such as the seven concentric spheres of ivory cut from a monolithic tusk, shared many attributes with today's mask fabrication. There is thoughtful design, critical work tool alignment, precise dimensional control, but, even when the customer truly is "King", there are also defects. Some of these pieces took years to make so I imagine that after say three years of toiling with an elephant tusk, if that last sphere of ivory has a crack, it is a bit analogous to finding a particle under the pellicle at final inspection on a 32nm metal 1 level: it makes you want to cry.

However, I saw many pieces at Augustus' place which either got past Quality or had a royal waiver. Repairs were evident which maybe says something about this customer Augustus. Did he work with his court craftsman closely in partnership to define what specifications were truly critical to his application? If the ceremonial ostrich egg urn with golden eagle claw foot stand, enameled memorial image of August the Strong on a horse and 25 carat ruby lid handle is scratched on the bottom, was he willing to look the other way?

Who knows for sure but he certainly recognized and appreciated fine things. We too should recognize and appreciate the incredible art, craft, engineering, and science which is evident in the fabrication of the modern-day photomask. I'm confident King August the Strong would have commissioned many photomasks for his collection if the readers of the BACUS News were in Dresden at the time.

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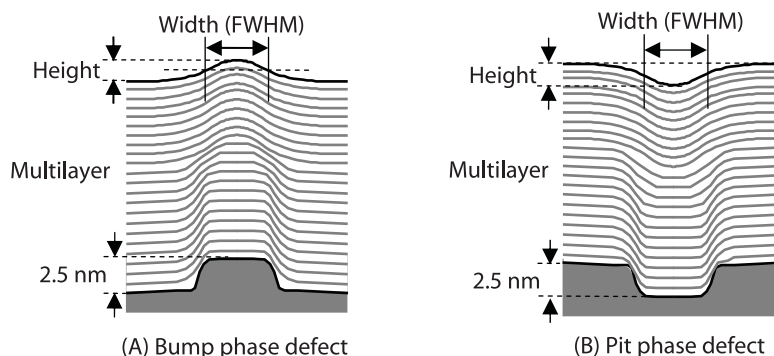


Figure 2. Structure and dimensions of programmed (A) bump and (B) pit phase defect.

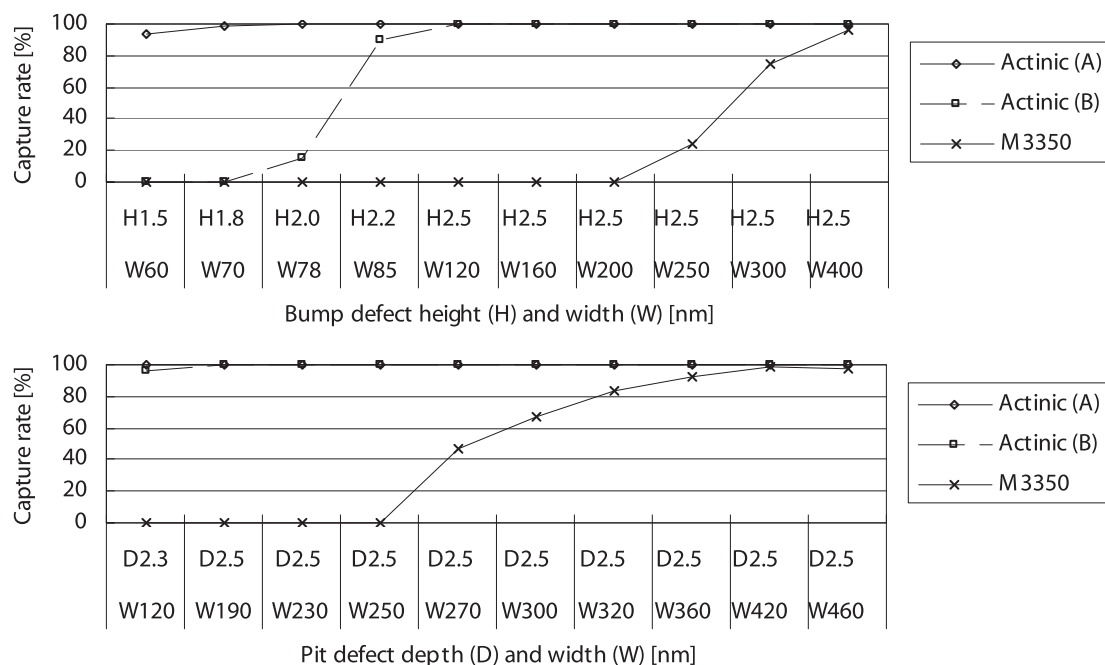


Figure 3. Capture rate of (1) bump and (2) pit phase defects with height, depth and width of defects measured by AFM.

1. Introduction

Extreme ultraviolet lithography (EUVL) is a promising technology for ULSI devices with a half-pitch (HP) of 32 nm and beyond. However, the fabrication of defect-free mask blanks and their inspection continues to be of ever growing concern for the implementation of EUVL. A multilayer phase defect is caused by a disordered multilayer, and is generated during the multilayer film growing process if a particle or a pit happens to reside on a quartz substrate surface. Because the defect is hardly noticeable on the mask blank surface with conventional inspection systems, an actinic (at wavelength) defect inspection technique has been pursued.¹⁻⁹

We have developed an actinic full-field inspection system to detect multilayer phase defects with dark field imaging. Based on our estimation of impact of a phase defect on a wafer for 32 nm (and below) HP devices, we set our target of inspection sensitivity to capture a phase defect caused by a 1.5 nm high and 40 nm wide protrusion on a multilayer surface. In this system, the light scattered from a defect on a mask blank surface propagating in the direction of a region lying between

the inner and outer NAs of the Schwarzschild optics reaches a CCD camera where the defect signal is captured as a spot signal brighter than the background intensity of the surrounding area. The mask blank stage of the system scans the full field of a mask blank to capture images with time delay integration (TDI) method. With the obtained images, the system can detect a defect as a spot signal brighter than a pre-determined threshold. Such a system has been fabricated and after its final tune-up and optimization, performance data of its inspection capability has now become available.

In this work, multilayer area on a mask with defects, that were not programmed defects, was inspected using the actinic full-field inspection system. The probabilities of the system for defect detection and false detection were evaluated. The same area was also inspected with a conventional inspection system, and then the inspection results from the two types of inspection systems were compared and evaluated. The detected defects were observed with AFM and SEM.

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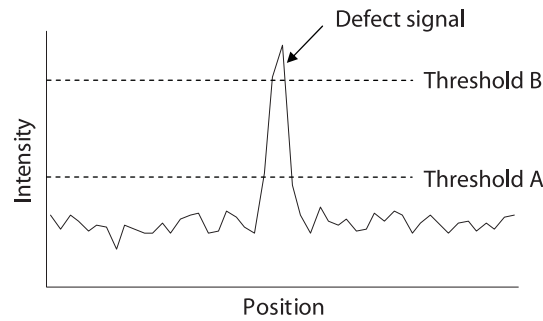


Figure 4. Signal intensity profile of a 2.5 nm-high 120 nm-wide bump defect and thresholds A and B for defect detection on the actinic inspection system.

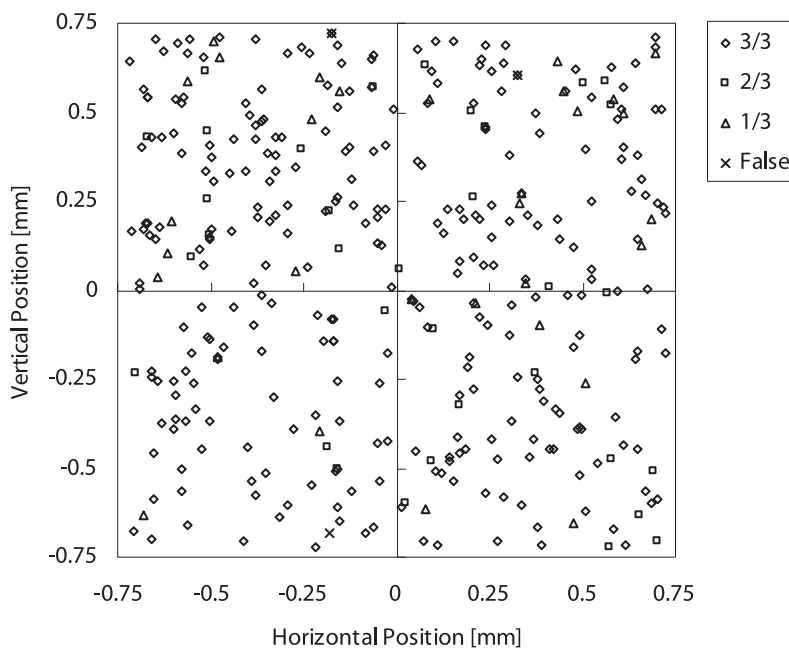


Figure 5. Detection map of 3 times inspections with the actinic inspection system.

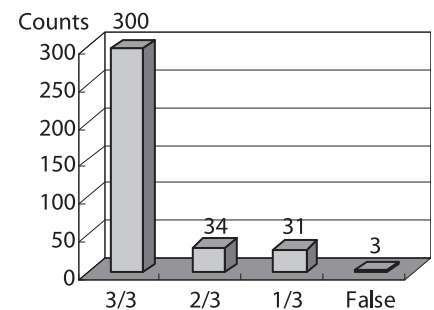


Figure 6. 3 times detection counts (3/3), 2 times detection counts (2/3), 1 time detection counts and false detection counts (False) in 3 times inspections.

2. Configuration of the Actinic Inspection System

2.1 Optical setup

The actinic full-field inspection system has evolved from an experimental work on MIRAI II project. The system consists of EUV light source, illumination optics containing ellipsoidal and plane mirrors, Schwarzschild optics for dark field imaging, and a EUV-sensitive backside-illuminated CCD camera.³⁻⁵ As described in Fig. 1, EUV light collected and polarized for 90 degrees on an ellipsoidal mirror (not shown) is reflected by a plane mirror (located under the convex mirror of a Schwarzschild optics) and illuminates a mask blank. In the presence of a defect on the mask blank surface the incident light is scattered by it and propagates in the direction of a region lying between the inner and outer NAs of the Schwarzschild optics and reaches the CCD camera where the defect signal is captured as a spot signal brighter than the background intensity of the surrounding area; whereas the reflected light from the mask blank remains shielded. In this system inner NA is set at 0.1, while the outer NA varies from 0.20 to 0.27. The pixel

size of the CCD is 500 nm at the object plane. For this work, the outer NA was set at 0.2.

2.2 Defect detection sensitivity

The defect detection sensitivity of the actinic inspection system was evaluated with programmed defects on a mask blank.^{10,11} The programmed defects consisted of 2.5 nm-high dots and 2.5 nm-deep holes on the quartz substrate. These dots and holes caused protrusions and depressions on the multilayer which took the form of bump- and pit-phase defects as shown in Fig. 2. The heights, depths, and full widths at the half maximum (FWHM) of these protrusions and depressions on the multilayer surface were measured by an atomic force microscope (AFM). The programmed defects were captured with a scan velocity of 1 mm/s using TDI method. The scan velocity of 1 mm/s corresponds to 10 hours a mask for an inspection. Figure 3 shows defect capture rates with respect to heights, depths, and widths of defects measured by AFM. The capture rate was calculated as:

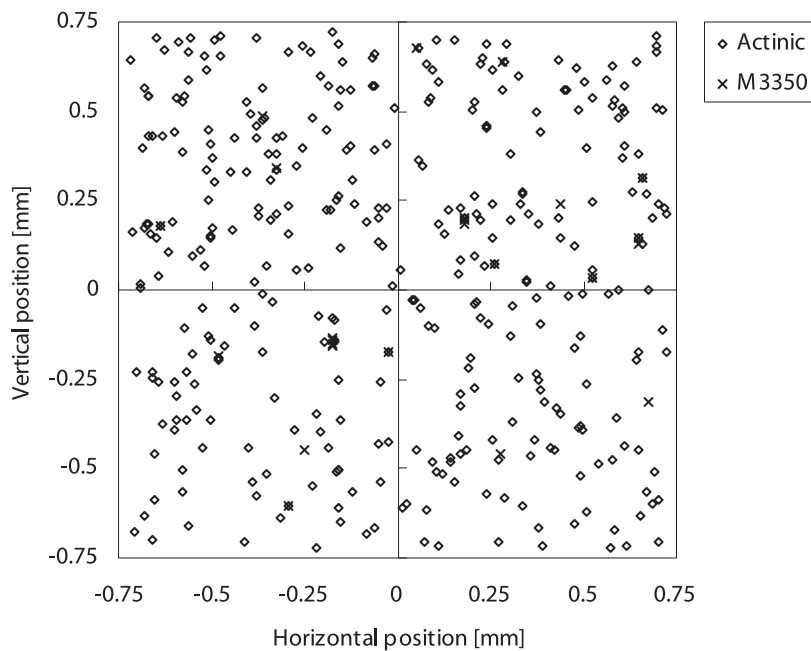


Figure 7. Defect map detected by the actinic inspection system and M3350.

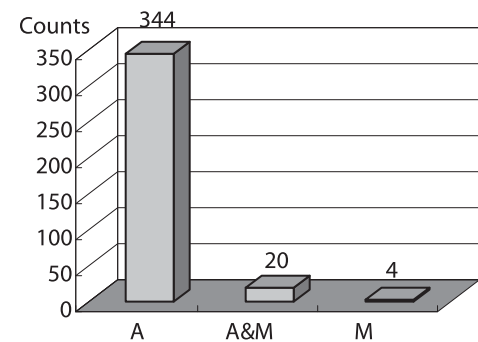


Figure 8. Number of defects detected only with the actinic system (A), detected with both systems (A&M), and detected only with M3350 (M).

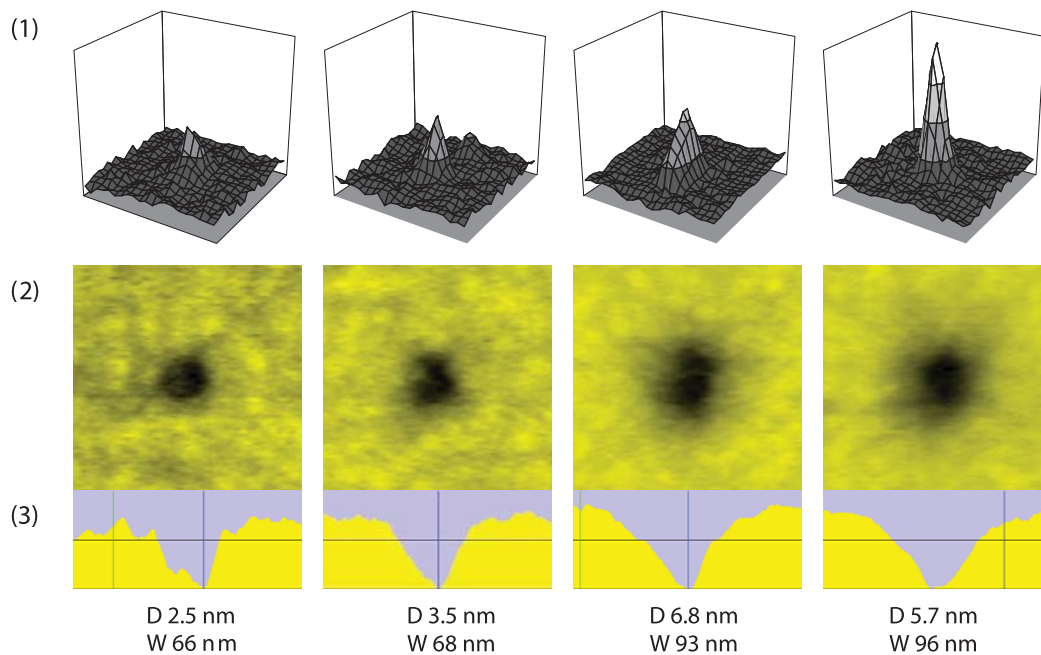


Figure 9. Four defects detected only with the actinic system. (1) Inspection images obtained with the actinic system, (2) top view images of AFM, (3) cross-sectional profile of AFM. Depth (D) and width (W) were measured by AFM.

Capture rate = Detected defect counts / Number of defects in a field of view

As shown in Fig.4, a signal with its intensity larger than a preset threshold is detected as a defect. For the evaluation of the defect detection sensitivity two thresholds, A (low threshold) and B (high threshold) were chosen. The lower threshold A was enabled to detect all programmed defects with almost 100% capture rate as shown in Fig. 3. However, in this case additional 26 false detections per mm² were also counted. In the case of the higher threshold B, the false detection count fell down

to less than one count per mm², although the capture rates for defects smaller than 80 nm-wide reduced to considerably below 100 %. In a manufacturing environment, minimization of false detection has been of industry's main focus, and hence threshold B was used in this work.

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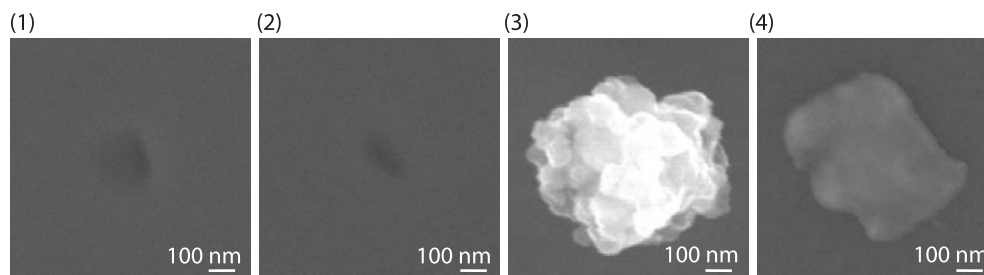


Figure 10. SEM images of (1), (2) phase defects and (3), (4) particles detected with the actinic system and M3350.

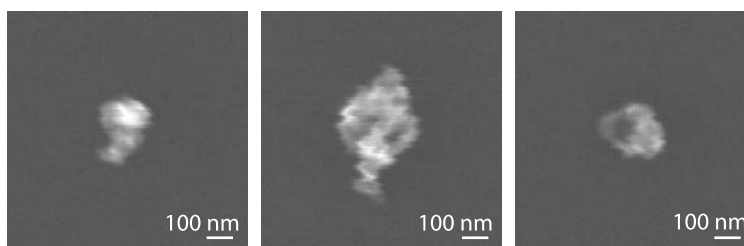


Figure 11. SEM images of particles detected only with M3350.

Inspection

3.1 Defect and false detection probability

A test mask was inspected three times with the actinic system and the probabilities of defect detection and false detection were evaluated. At the center of the mask a 1.5 mm square (containing no absorber) was chosen for the inspections. The multilayer was deposited by ASET in 2005. The scan velocity was 1mm/s, and threshold for defect detection was set at a higher value B as shown in Fig. 4. A detection map obtained from the three times inspections is shown Fig. 5. The detection counts from the first, second and third inspections came out to be 331, 330 and 331. The total number of defects identified by three times inspections was 368. Among the 368 defects, 300 of them were detected three times, 34 were detected twice, 31 were detected once, and there were 3 counts of false detection as shown in Fig. 6. This means that 81.5 % of the total number indicate 100 % detection probability, while 0.8 % of them indicate false detection.

3.2 Comparison with a conventional inspection system

The same area inspected in the above experiment was then also inspected with M3350 (Lasertec) equipped with 488 nm wavelength light source for inspection. Using the inspection conditions normally employed, the defect sensitivity was evaluated by monitoring the capture rates of the programmed defects as shown in Fig. 3. The defects detected with the actinic system and M3350 (except false detection) are shown in Fig. 7. The combined value of the total number of defects detected with both tools was 368. As shown in Fig. 8, the number of defects that were detected only with the actinic system was 344, that of defects detected with both systems was 20, and that of defects detected only with M3350 was 4. This means that 94 % of total defects were detected only with the actinic system, while 1.1 % of the total defects were detected only with M3350.

3.3 Defect review by AFM and SEM

Surface profiles of the defects detected only with the actinic system were observed with AFM. Figure 9 shows examples of four defect images obtained by the actinic system and AFM. All four defects were “pit” phase defects. The depths and the widths (FWHM) of the defects were measured by AFM, shown in Fig. 9. The result indicates that phase defects smaller than 100 nm could only be detected with the actinic inspection system.

Defects detected with both inspection systems were observed with SEM. Among a total of 20 defects, 9 were phase defects, 6 were actual particles, and the rest were not found by the SEM. Figure 10 shows SEM images of the phase defects and particles. The result indicates that phase defects larger than 100 nm, and particles larger than 200 nm could be detected with both of the inspection systems.

Defects detected only with M3350 were also observed with SEM. From these defects, 3 of them were particles (not phase defects), and 1 defect was not found. Figure 11 shows SEM images of those particles. The result means that a particle smaller than 100 nm cannot be detected with the actinic system. We believe that these particles generate very little scattering light and their signal in the dark field turns out to be very weak to be detected by the actinic system.

4. Summary

A non-commercial mask was inspected with an actinic full-field inspection system using a threshold for low false detection which resulted in the detection of real defects. A 1.5 mm square area (containing no absorber) was inspected three times, and probabilities of defect detection and false detection were evaluated. Of the total numbers detected, 81.5 % of them exhibited 100 % probabilities of detection while 0.8 % of them indicated false detection.

The inspection result was compared with that of a conventional inspection system. Among the defects that were detected, 94 % of them could be detected only with the actinic system, while 1.1 % of them could be detected only with the conventional system. The detected defects were observed with AFM and SEM. Phase defects smaller than 100 nm were detected only with the actinic system, while particles smaller than 200 nm were detected only with the conventional inspection system.

At this point, high defect sensitivity with no false detection is not attainable. We attribute this difficulty to noise in the CCD camera which we will be able to fix.

5. Acknowledgment

The authors are grateful to HOYA Corporation for the programmed defect mask fabrication and AFM measurement.

They thank Kazuto Kinoshita and Satoshi Gonda of national institute of AIST for AFM observation of the inspected mask. This work was supported by New Energy and Industrial Technology Development Organization (NEDO).

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Industry Briefs

■ Nanocrystals bid to extend photolithography (with double-patterning)

By **R. Colin Johnson**, EE Times

Optical lithography can be extended below 32 nm, according to Pixelligent Technologies LLC (when one decides to use double-patterning). Pixelligent has developed a nanocrystalline material that it says enhances the resolution of existing photolithography equipment. The company recently closed a \$2 million round of equity financing to commercialize its nanocrystals, for applications in optical lithography and as nanocomposite coatings for microelectronics.

"We are using nanotechnology to develop new materials for photolithography," said Greg Cooper, founder and president of Pixelligent (College Park, Md.). "The industry has pushed optical lithography nearly as far as it will go, but we believe we can extend its lifetime with new materials that have unique optical properties that don't exist today." Pixelligent's secret sauce involves the fabrication of nonsilicon nanocrystals with custom-designed properties. The company declined to identify the exact composition of its proprietary nanoparticles, except to say that they are nonsilicon.

By combining the semiconducting nanocrystals with lithographic polymers, Pixelligent claims traditional resists can be improved so that they can image much finer lines. The company also claims its nanocrystal coatings result in higher yields, lower materials costs and improved throughput, all while using existing chip fabrication equipment.

National Institute of Standards and Technology's Advanced Technology Program (ATP) awarded Pixelligent a \$2 million contract in 2007, and the company has received a total of \$600,000 in other awards. Pixelligent developed a semiconductor nanocrystal-based reversible contrast enhancement layer (R-CEL) using a unique photobleachable material that's said to allow double patterning of wafers at ultrahigh resolutions. (193-nanometer-wavelength light can image features at 65 nm, but extending that capability below 45 nm requires double patterning). Pixelligent says the R-CEL allows ultrahigh resolutions by virtue of the reversible photobleaching effect, which prevents interference between the two exposures. The R-CEL can be selectively bleached in one pattern to allow the lithography light to go through, then reversed to an opaque state and rebleached for the second-stage pattern.

■ TSMC weighs in on e-beam, EUV litho

Foundry giant Taiwan Semiconductor Manufacturing Co. Ltd is still backing two horses in the race to the next lithography: extreme ultraviolet lithography (EUVL) and clustered electron-beam. Jack Sun, VP of R&D at TSMC, revealed that the idea that future lithography machines could cost \$40 million or \$60 million each is a concern to TSMC.

"TSMC will push for cost-effective lithography," said Sun as he proposed the possibility that clustered direct-write e-beam lithography could approach 100 wafers per hour throughput, a benchmark of industrial production using optical lithography. TSMC is currently investigating both EUV litho with ASML Holding NV and e-beam lithography with Mapper Lithography BV. ASML has an EUV advanced development tool installed at IMEC while Mapper is delivering a 300mm maskless e-beam lithography platform to CEA-Leti in Grenoble.

Apparently showing a little of bit of the carrot and the stick to leading EUV lithography equipment developer. Sun said: "We welcome proposals in EUV to move from 0.25 NA to 0.35 NA and take throughput to 100 wafers per hour." ASML is said to have five orders for its first pre-production EUV tool the NXE 3100 and TSMC along with Intel is expected to be among the recipients.

But Sun also listed some of the challenges remaining; EUV source power, mask making and mask integrity and defect inspection. And he went on to present how Mapper's technology could provide for 13,000 individual beams in a chamber to expose an IC masklessly at a rate of 10 wafers per hour and the possibility of clustering ten such machines together to achieve 100 wafers per hour. Sun emphasized that the need to work on 22nm CMOS, EUV and e-beam was one of the reasons the company was formally creating an R&D center in Europe based at IMEC in Leuven.

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